

The Palladium Component of an Immobilized Sonogashira Catalyst System: New Insights by Multinuclear HRMAS NMR Spectroscopy

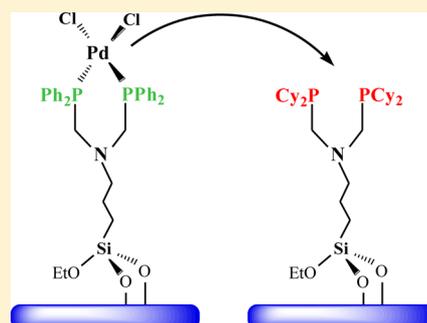
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S Supporting Information

ABSTRACT: Multinuclear one- and two-dimensional HRMAS NMR spectroscopy has been used to investigate the palladium component of a Sonogashira catalyst system immobilized on silica by diverse bifunctional phosphine linkers incorporating Si(OEt)₃ groups. The coordinating strengths of these mono- and bidentate phosphine ligands have been assayed in situ by competition experiments monitored with ³¹P HRMAS NMR spectroscopy. The ligand best retaining and scavenging the PdCl₂ fragment has been determined to be immobilized (EtO)₃Si(CH₂)₃N-(CH₂PCy₂)₂, while silica-bound (EtO)₃Si(CH₂)₃NH₂ and (EtO)₃Si(CH₂)₃PPh₂ led to leaching. The coordinating strengths of the immobilized ligands have been correlated with the catalytic activities of the corresponding immobilized Sonogashira catalyst systems regarding the coupling of phenylacetylene with iodobenzene.



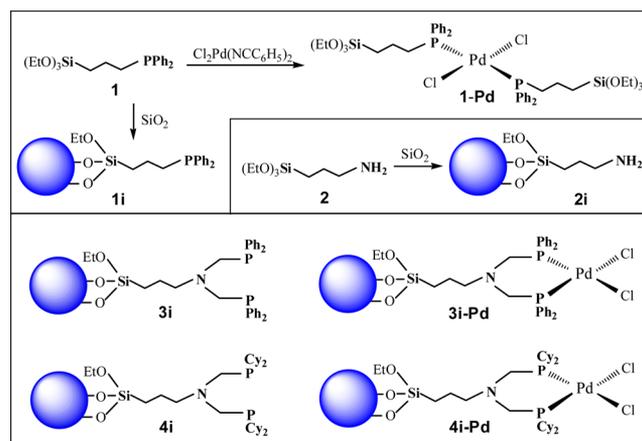
Carbon-carbon bond-forming reactions have dominated homogeneous catalysis over the past decade,¹ and the Pd(0)/Cu(I)-catalyzed Sonogashira coupling of aryl halides with acetylenes represents one of the most important catalytic reactions.² Despite its impact, however, detailed mechanistic studies remain scarce² because in solution a plethora of species, including nanoparticles,^{3a,b} can contribute to the catalytic activity. Immobilizing the catalysts enables one to distinguish between the different species and their effects.³ Tethering a catalyst to a solid support such as silica⁴ offers the additional advantage that the catalysts can easily be removed from the reaction mixtures and recycled many times.³

In this contribution, we demonstrate that, by using the line-narrowing HRMAS technique,⁵ surface-bound catalysts can be fully characterized and their leaching behavior, dynamics, and linker preferences determined in a straightforward manner. This allows the coordinating strengths of the linkers to be correlated with the activities of the corresponding immobilized Sonogashira catalyst systems.

The molecular and immobilized linkers and metal complexes utilized in this contribution include the species depicted in Scheme 1. Their syntheses have been described earlier.^{5a,b} All immobilized linkers and metal complexes are amenable to ³¹P NMR analysis, as shown for **3i** (Figure 1). Much narrower lines are obtained with the HRMAS measurements of slurries (middle spectrum) than with the classical CP/MAS NMR of the dry materials (top spectrum).

The more polar and less viscous the solvents used for the slurries, the narrower the ³¹P HRMAS signals (Table 1), in accordance with earlier results obtained without MAS.⁶ The $\delta(^{31}\text{P})$ values show only the usual small differences due to solvent effects. For the following experiments acetone-*d*₆ is

Scheme 1. Synthesis of 1-Pd and Immobilization of 1 and 2 (Top) and Structures of 3i, 4i, 3i-Pd, and 4i-Pd (Bottom)



chosen because it provides narrow lines without replacing ligands at the metal centers.^{5b}

In addition to NMR, **1-Pd** could be characterized by a single-crystal X-ray structure, although compounds incorporating ligands with alkyl chains and ethoxysilane groups usually prefer to form viscous oils. The structure shows that the ligands assume trans positions in a square-planar coordination geometry (Figure 2).⁷ Although both *cis* and *trans* isomers of palladium bis(phosphine) complexes are possible,⁸ the steric demand of the phosphine substituents favors *trans* substitution. The Cl–Pd–P angles are 93.2 and 86.8°. The ethoxysilylpropyl

Received: November 17, 2014

Published: November 25, 2014

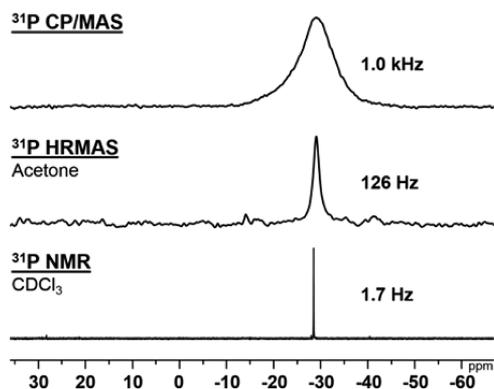


Figure 1. ^{31}P CP/MAS NMR spectrum and signal half-widths of immobilized chelate ligand **3i** on silica ($\nu_{\text{rot}} = 4$ kHz), ^{31}P HRMAS of **3i** as a slurry in acetone (2 kHz), and $^{31}\text{P}\{^1\text{H}\}$ NMR spectrum of molecular **3** dissolved in CDCl_3 .

Table 1. ^{31}P HRMAS NMR Chemical Shifts $\delta(^{31}\text{P})$ and Half-Widths $\nu_{1/2}$ of **3i** in the Indicated Solvents^a

solvent	$\delta(^{31}\text{P})$ (ppm)	$\nu_{1/2}$ (Hz)
diethyl ether	-29.52	111
THF	-29.41	115
methanol	-29.63	119
acetone	-29.65	126
acetonitrile	-29.75	128
DMF	-29.63	138
dichloromethane	-29.55	142
toluene	-29.33	265
hexanes	-29.19	944

^aThe surface coverage for all samples is 0.103 g (0.167 mmol) of **3** on 1.0 g of SiO_2 , corresponding to 13.4 molecules per 100 nm^2 .

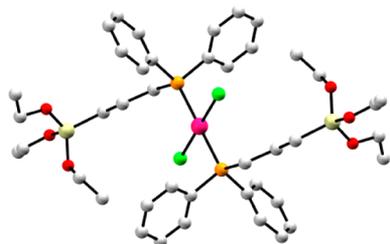


Figure 2. X-ray crystal structure of *trans*- $\text{Cl}_2\text{Pd}[\text{PPh}_2(\text{CH}_2)_3\text{Si}(\text{OEt})_3]_2$ (**1-Pd**). Hydrogen atoms are omitted for clarity.⁷

substituents point in opposite directions, with an $\text{H}_2\text{C}-\text{P}\cdots\text{P}-\text{CH}_2$ dihedral angle of 180° . This result is important for the interpretation of the HRMAS spectra and dynamic effects, as discussed below.

Complex **1-Pd** was immobilized on silica according to the standard procedure to give **1i-Pd**.^{5a,b} The latter was thoroughly characterized by one- and two-dimensional HRMAS NMR spectroscopy.^{5a,c} Figure 3 depicts the $^1\text{H}, ^1\text{H}$ HRMAS TOCSY spectrum. The connectivity of the alkyl ^1H signals of the propyl chain can clearly be seen, as well as the OCH_2 and CH_3 resonances of residual OEt groups^{5c,9} and their cross peaks. The large intensities of the ethoxy signals in the HRMAS TOCSY spectrum (Figure 3) indicates that only one of the triethoxysilyl groups of **1-Pd** is actually bound to the support, while the second triethoxysilyl group points in the opposite direction and is mobilized by the solvent.

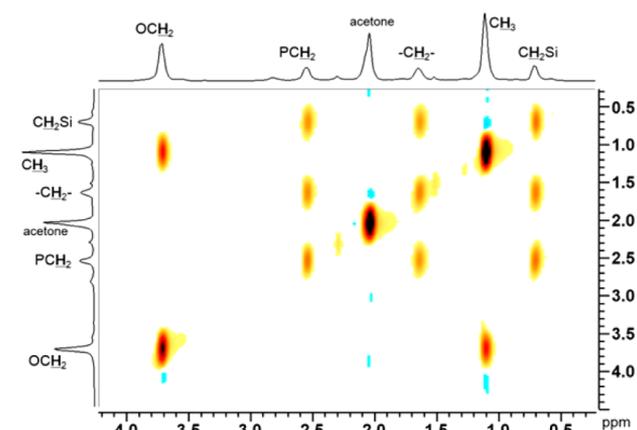


Figure 3. $^1\text{H}, ^1\text{H}$ HRMAS TOCSY NMR^{5c} spectrum of an acetone- d_6 slurry of the immobilized complex **1i-Pd**.

The favorable resolution of the ^1H and ^{13}C HRMAS spectra allows a $^{13}\text{C}, ^1\text{H}$ HRMAS COSY spectrum of **1i-Pd** to be recorded (Figure 4). The $\delta(^{13}\text{C})$ values of all alkyl and aryl

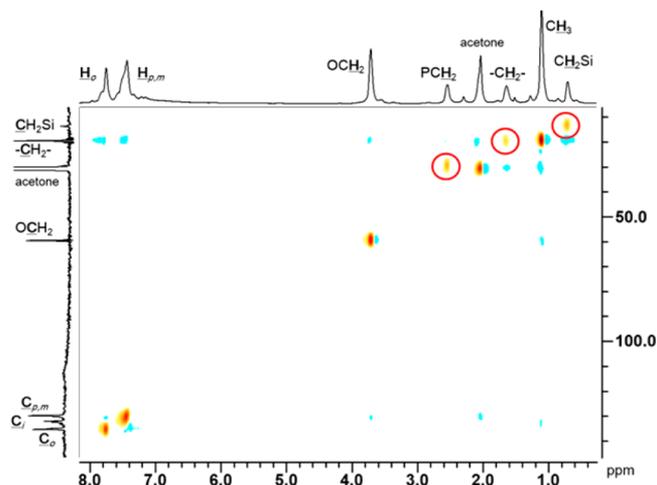


Figure 4. $^{13}\text{C}, ^1\text{H}$ HRMAS COSY NMR^{5c} spectrum of an acetone- d_6 slurry of immobilized complex **1i-Pd**.

carbon signals of the ligand can be obtained via the corresponding cross peaks in the spectrum. The presence of residual OEt groups is proven by the correlations of the ^1H NMR signals with the corresponding ^{13}C ethoxysilane signals.^{5c,9} This further corroborates the assumption that only one of the linkers is bound to the support surface, as established previously for immobilized Ni complexes.¹⁰ The *trans* coordination and steric demand of the linkers (Figure 2) favor this scenario.

Having thoroughly characterized all immobilized species, next we sought to study (a) whether the PdCl_2 fragment can be detached from a given phosphine linker and (b) whether it can be scavenged again by a more strongly coordinating linker in situ, or whether it is adsorbed on the silica surface or forms clusters, in this way leaving the “radar screen” of the HRMAS measurement. In the favorable case of recapturing the PdCl_2 fragment, a ranking of the ligands with respect to their coordinating strengths^{1d,e,11} is desired. In order to investigate (a) and (b), competition experiments have been performed, where two different linkers or Pd complexes are immobilized on separate silica batches. Then the batches are mixed and

combined with acetone.¹² The possibility of subsequent PdCl₂ migration is assayed in situ over time by ³¹P HRMAS spectroscopy.^{5b} Representative spectra are displayed in Figure 5.

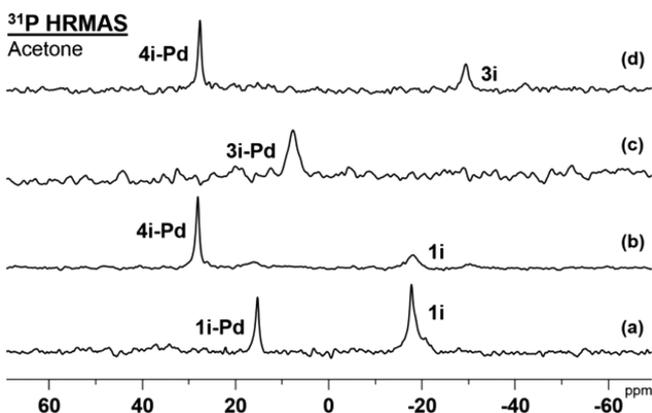


Figure 5. ³¹P HRMAS spectra of the following batches after being mixed together and combined with acetone: (a) **1i-Pd** and **1i**; (b) **4i-Pd** and **1i**; (c) **3i-Pd** and **2i**; (d) **4i-Pd** and **3i**.

Regarding the batches **1i-Pd** and **1i**, initially both ³¹P HRMAS signals are present at 14.8 and −18.2 ppm (Figure 5a), with small half-widths of 24 and 202 Hz, respectively. Over the course of several hours their intensities diminish and a broad resonance emerges, indicating that the palladium center has migrated from one batch to the other and is diluted on the surfaces of both batches, displaying the dynamic “palladium hopping” process described earlier.^{5a} If only one linker per molecule is attached to the surface, as the X-ray structure of **1-Pd** and the signals of residual ethoxysilane groups in the 2D HRMAS spectra of **1i-Pd** suggest, this process might be facilitated. The “Pd hopping” can be stopped by adding borane as a quenching group,^{5a} resulting in an intense signal at 14.4 ppm for **1i-BH₃**. In contrast, no dynamic process is observed when **4i-Pd** is mixed with **4i**, which means that palladium does not leave this chelate ligand.

When batches of **3i-Pd** or **4i-Pd** (Figure 5b) are mixed with **1i**, palladium remains coordinated to the chelate linkers even after days. Only the narrow signals of **3i-Pd** (6.8 ppm, 53 Hz) and **4i-Pd** (28 ppm, 18 Hz) are visible in the spectra in addition to the resonance of **1i**. When the experiment is reversed and **4i** is mixed with **1i-Pd**, the signal of **4i-Pd** is immediately apparent. This means that the migration of palladium from the monodentate to the chelate linker takes place within minutes. A prerequisite for this result is that PdCl₂ is readily leaching from **1i-Pd** but is not permanently adsorbed on the silica surface.

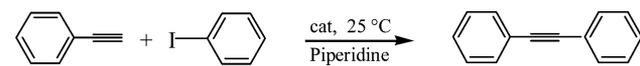
When the chelate complex **3i-Pd** is competing with the immobilized amine linker **2i**, it retains the coordinated Pd and only the signal for **3i-Pd**, with no trace of **3i**, is visible in the ³¹P HRMAS spectrum (Figure 5c). Mixing batches of **3i** with **2i-Pd** results in the signal of **3i-Pd** emerging within 1 h, which means that the leaching of the palladium from the monodentate amine linker and the scavenging by the chelate linker **3i** are fast processes.

Finally, the chelate linkers **3i** and **4i** were set up to compete with each other. When **4i-Pd** is mixed with **3i**, the spectrum shown in Figure 5d persists with an undiminished intensity of the narrow signal for **3i** at −29.3 ppm. In summary, the competition experiments show that the ligand retaining and

scavenging the PdCl₂ fragment best is **4i**, followed by **3i**, while **1i-Pd** and **2i-Pd** are both prone to leaching.

We sought to apply the preceding data to a Sonogashira cross-coupling, with phenylacetylene and iodobenzene as the substrates (Scheme 2).¹³ Here the goal was not to obtain a

Scheme 2. Sonogashira Reaction Used for Testing the Catalytic Activity of Immobilized Catalysts



catalyst system with optimal catalytic activity and recyclability, as it has been achieved earlier.^{5a,b} Rather, we sought to investigate the impact of the palladium leaching on the catalytic activity of the immobilized Sonogashira catalyst system.

Indeed, a correlation can be established between the coordinating strength of the immobilized linker for the PdCl₂ fragment and the corresponding catalytic activity of the Sonogashira catalyst system. The more strongly the phosphine linker coordinates to the Pd complex, the lower the catalytic activity. While complex **3i-Pd**, for example, in combination with CuI leads to quantitative conversion of the substrates to the product within 6 h at room temperature,¹³ the catalyst **4i-Pd** only achieves 13% conversion under the same conditions. This proves that, in order to generate the catalytically active system, the palladium component has to become detached from the support and achieve contact with the copper complex. A 2/1 Pd/Cu ratio was found to give optimal yields. If the palladium is tethered too firmly to the support by a strongly coordinating linker, this ratio cannot be realized, and catalysis is impeded.

In conclusion, it has been demonstrated that multinuclear one- and two-dimensional NMR techniques are indispensable for characterizing surface-bound species of the type shown in Scheme 1. An X-ray structure of a palladium complex proves the trans coordination of the monodentate phosphine ligands and explains the presence of residual ethoxy group signals in the HRMAS NMR spectra of the corresponding immobilized species. Competition experiments between different surface-bound linkers demonstrate that in the presence of a solvent the PdCl₂ fragment migrates to the chelate ligand with the strongest coordination. However, this leads to the least active catalyst. Therefore, it is concluded that an active immobilized Sonogashira catalyst system needs to allow for the palladium to come into physical contact with the copper component, with the preferred Pd/Cu ratio being 2/1. In future studies the palladium and copper components will be incorporated in the same “designer” ligand on a molecular scale, where they reside in close contact to each other, in different ratios.

■ ASSOCIATED CONTENT

Supporting Information

A CIF file giving crystallographic data for *trans*-Cl₂Pd-[PPh₂(CH₂)₃Si(OEt)₃]₂ (**1-Pd**). This material is available free of charge via the Internet at <http://pubs.acs.org>. CCDC 921482 also contains supplementary crystallographic data for the X-ray structure of **1-Pd**.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This material is based upon work supported by The Robert A. Welch Foundation (A-1706), the National Science Foundation (CHE-0911207, CHE-1300208, CHE-0840464), and the APPEAL Consortium at Texas A&M University.

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(4) Merck silica (average pore diameter 40 Å, particle size 0.06–0.2 mm, specific surface area 750 m² g⁻¹), predried for 4 days in vacuo at 300 °C.

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(7) Yellow crystals of **1-Pd** (CCDC 921482) are obtained by cooling its solution in a mixture of toluene and pentane (1/10) to –20 °C. C₄₂H₆₂Cl₂O₆P₂PdSi₂, unit cell parameters: *a* = 13.564(2) Å, *b* = 8.8285(14) Å, *c* = 20.404(3) Å, space group P2₁/c.

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(12) Representative procedure: the immobilized ligand **3i** (0.022 g, 0.0288 mmol; 0.131 mmol/g of SiO₂) was combined in a 1/1 ratio with the immobilized complex **4i** (0.020 g, 0.0288 mmol; 0.147 mmol/g of SiO₂) in a HRMAS rotor and mixed thoroughly. After acetone was placed in the rotor and the rotor was sealed, the first measurement was started. Spectra were recorded every 1024 scans (ca. 1.5 h) using a block averaging program.

(13) Representative catalytic procedure for **3i-Pd**: in a Schlenk flask under an inert gas, 0.0895 g (0.123 mmol immobilized Pd complex) of **3i-Pd** was combined with 0.0012 g (0.0063 mmol) of CuI, dissolved in a mixture of 2.5 mL of toluene and 2.5 mL of piperidine. After 0.17 mL (1.53 mmol) of freshly distilled phenylacetylene and 0.14 mL (1.27 mmol) of iodobenzene were added, the progress of the reaction was monitored at 25 °C via GC. For this purpose 0.1 mL aliquots of the reaction mixture were sampled at 1 h time intervals and filtered

through a Pasteur pipet, containing ca. 100 mg of silica gel, with toluene as the eluent.